APPENDIX H

HISTORICAL FREQUENCY OF OCCURRENCE ASSESSMENT OF EMBANKMENT FAILURE DUE TO PIPING

H-1. Introduction. Currently there are two different piping conditions identified that require different methods of analysis: 1) piping directly related to pool elevation which can be correlated to piezometric or seepage flow data, and 2) piping related to a complex seepage condition within the dam or its foundation that cannot be evaluated solely by analytical methods. Each of these piping conditions could be related to the development of higher pore pressures within the embankment resulting in a loss of shear strength and a resulting slope stability failure. However, the following discussion will be limited to seepage conditions leading to incidents or failure as a result of piping.

H-2. Piping Failure. An extensive analysis of piping has been conducted in the report *Analysis of Embankment Dam Incidents,* M. A. Foster, R. Fell, and M. Spanagle, UNICV Report No. R-374, September 1998. Following is the abstract from the report:

This report details the results of a statistical analysis of failures and accidents of embankment dams, specifically concentrating on incidents involving piping and slope stability. The aim of the study was to extend the existing compilations of dam incidents to include more details on the characteristics of the dams including dam zoning; filters, core soil types; compaction; foundation cutoff; and foundation geology. An assessment of the characteristics of the world population of dams was performed to assess the relative influence particular factors have on the likelihood of piping and slope instability.

Using the results of this analysis, a method was developed for estimating the probability of failure of embankment dams by piping taking into account the characteristics of the dam, age of the dam, dam performance and level of monitoring and surveillance. The so called “UNSW method” is intended to be used for preliminary risk assessments.

H-3. Procedure. Use of the procedures presented in the referenced report will generate an average annual probability of failure by piping which can then be used directly in analysis of risk associated with damages or loss of life. The procedure consists of the following steps:

(1) Identify the embankment zoning category shown on Figure H-1 (Figure 3.1 from UNSW report) that most closely matches the zoning of the dam to be evaluated.

(2) Determine the average annual probabilities of failure using Table H-1 (Table 11.1from UNSW report) for each of three modes of failure:

- -Piping through the embankment
- -Piping through the foundation
- -Piping from the embankment into the foundation

Select value corresponding to the age of the dam (i.e. less than or greater than 5 years).

(3) Calculate the weighting factors accounting for the characteristics of the dam for each of the three failure modes using Tables H-2 through H-4(Tables 11.2 through 11.4 from the UNSW report). The weighting factor for each mode of failure is obtained by multiplying the individual weighting factors for each characteristic (i.e. embankment filters, core compaction, foundation treatment, etc.)

(4) Calculate the overall probability of failure by piping by summing the probabilities for each of the three modes.

H-4. Use of Results.

a. As previously stated, the results of the above calculation will produce an average annual probability of failure by piping that can be used in further risk assessment calculations. The results may also be used in an assessment of the probability of piping failure compared to other dams of similar size, zoning, composition, geologic setting, operational history, etc. In this evaluation, the absolute value of probability is less important than the relative comparison of probability values. The method is intended to identify a dam whose probability of piping failure clearly stands out from other comparable dams. Such an analysis was recently (August 2000) conducted by the Baltimore District on Waterbury Dam. The results of the UNSW analysis for Waterbury were compared to several comparable Baltimore District dams located at sites with similar glacial geologic conditions. The analysis indicated that the probability of failure of Waterbury by piping through the embankment was more than 4000 times the probability of failure of comparable Baltimore District dams. Following is a tabulation of the results of that analysis:

Table H-5. Probability of Failure by Piping Through the Embankment.

WEIGHTING FACTORS (with typical range of values)	ASSIGNED WEIGHTING FACTOR VALUE						
	Waterbury (current condition)	**Waterbury (after repairs)**	Tioga-Hammond	Whitney Point	Cowanesque	Stillwater	Average of four Baltimore Dams
Zoning for dams after 5 years of operation (see Table 11.1)	24×10^{-6}	24×10^{-6}	25×10^{-6}	25×10^{-6}	25×10^{-6}	160×10^{-6}	5.875×10^{-5}
Embankment Filters (0.02 to 2.0)	2	0.02	0.02	0.2	0.02	0.02	0.065
Core Geological Origin (0.5 to 1.5)	1.5	1.5	1.0	1.0	0.5	1.0	0.875
Core Soil Type (0.3 to 5.0)	2.5	2.5	0.8	0.8	0.8	0.8	0.8
Compaction (0.5 to 5.0)	0.7	0.7	0.5	0.5	0.5	0.5	0.5
Conduits (0.5 to 5.0)	2.5	0.8	0.5	0.5	0.8	0.5	0.575
Foundation Treatment (0.9 to 2.0)	**5** to 10 **	0.9	0.9	0.9	0.9	0.9	0.9
Observations of Seepage (0.5 to 10.0)	**2** to 10	1.0	0.7	1.0	0.7	0.7	0.775
Monitoring and Surveillance (0.5 to 2.0)	0.5	0.5	0.8	0.8	0.8	0.8	0.8
W_E (total weighting factor)	6.56×10^{1}	1.9×10^{-2}	2.02×10^{-3}	2.88×10^{-2}	1.61×10^{-3}	2.02×10^{-3}	7.30×10^{-3}
P_eW_E (weighted probability)	$\mathbf{1.58 \times 10^{-3}}$	$\mathbf{4.54 \times 10^{-7}}$	5.04×10^{-8}	7.20×10^{-7}	4.03×10^{-8}	3.23×10^{-7}	$\mathbf{4.29 \times 10^{-7}}$

**Although it is greater than the maximum recommended value of 2, a foundation treatment weighting factor value of 5 was used based on the extreme foundation condition within the gorge of Waterbury Dam. Even this value may underestimate the potential negative influence of the gorge conditions compared with other dams that have failed by piping.

b. The analysis method was also applied to potential remedial alternatives to assess the relative benefits of the alternatives. The results of that analysis are reflected in the third column of the above tabulation showing the probability of failure of the dam after application of the proposed remedial repairs. The UNSW methodology may be used to provide a reasonable assessment of potential structural repairs (i.e. reconstruction of all or part of the dam or a cutoff wall), but cannot be used to assess the risk reduction associated with non-structural solutions (i.e. permanent reservoir drawdown or increased discharge capacity).

Assessment of Embankment Failure Due to Piping

The following procedure for determining the probability of failure by piping is based on the work by Foster, Fell, and Spanagle in the report published by the University of New South Wales (UNSW). References to tables or figures are from that report.

1. Identify the cross section on Fig H-1 (UNSW Figure 3.1) that most closely matches the section of the dam.

2. Select the base probability of failure of the dam by piping from Table H-1 (UNWS method Table 11.1) taking into account both the dam section and the age of the dam.

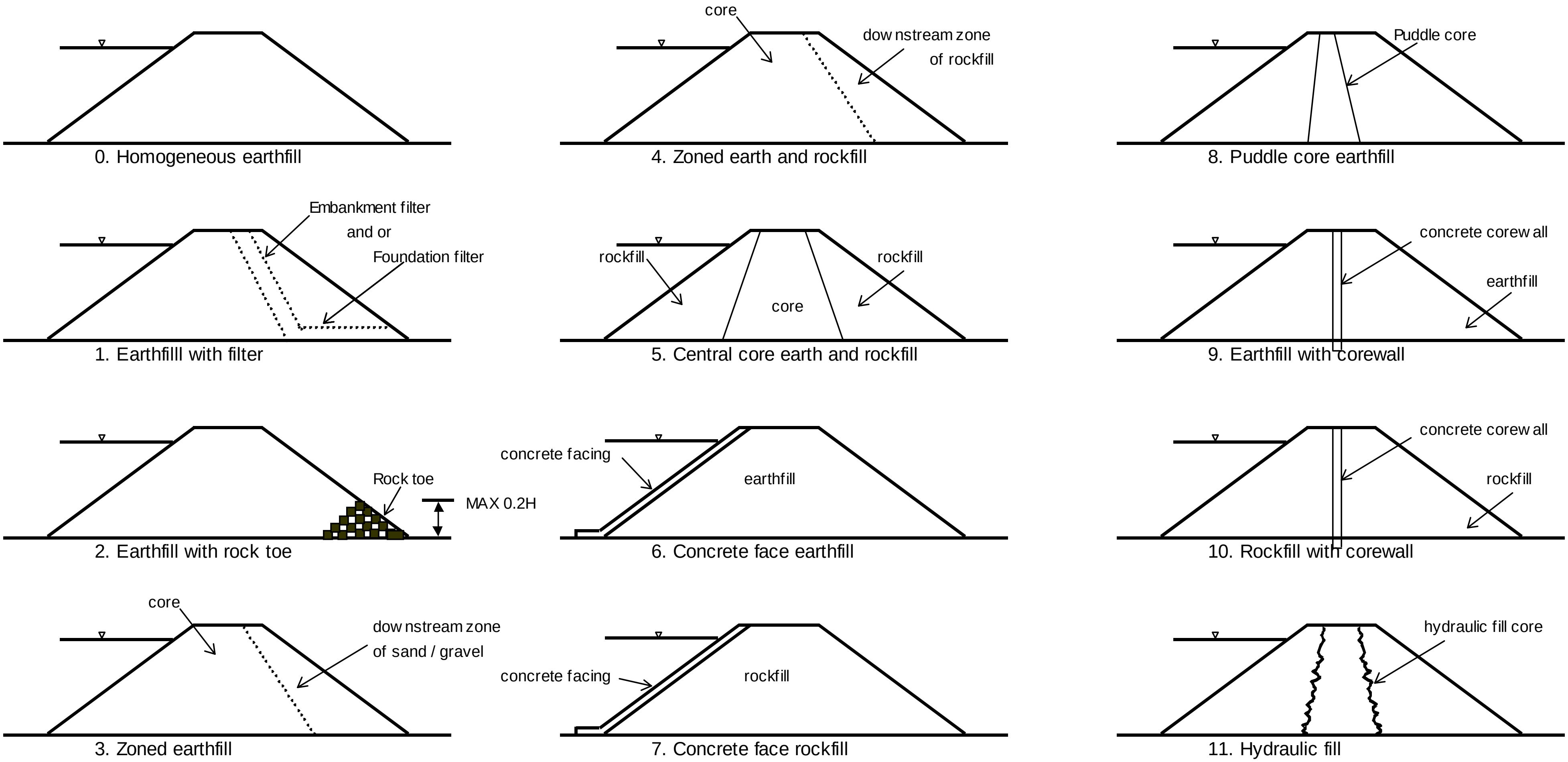
3. Determine the appropriate weighting factor from the list in Tables H-2 through H-4 (UNSW method Tables 11.2 through 11.4) for each of the 3 potential modes of piping failure (i.e. piping through the foundation, piping through the embankment, or piping from the embankment into the foundation).

4. Compute the probability of failure for each of the 3 potential failure modes.

5. Sum the 3 probability values to find the overall probability of failure by piping from all potential modes.

6. Perform the same analysis on other comparable dams considering size, zoning, site geology, construction methodology, and operation. Compare these results to that computed for the dam in question.

7. Comparison of probabilities can be used directly to assess the relative probability of failure, or computed probabilities can be used as input to further computations related to economic or environmental damage, or loss of life. Suggest use of a pool elevation that reflects the upper elevations of average annual range of pool elevations to determine consequences.



Dam zoning categories (UNSW Figure 3.1:)

Figure H-1

Reference : **Foster, Spanagle and Fell 1998**

Table H-1
(Table 11.1 UNSW): Average Probability of Failure of Embankment Dams by Mode of Piping and Dam Zoning.

ZONING CATEGORY	EMBANKMENT			FOUNDATION			EMBANKMENT INTO FOUNDATION		
	Average P_{Te} ($x10^{-3}$)	Average Annual P_e ($x10^{-6}$)		Average P_{Tf} ($x10^{-3}$)	Average Annual P_f ($x10^{-6}$)		Average P_{Tef} ($x10^{-3}$)	Average Annual P_{ef} ($x10^{-6}$)	
		First 5 Years Operation	After 5 Years Operation		First 5 Years Operation	After 5 Years Operation		First 5 Years Operation	After 5 Years Operation
Homogenous earthfill	**16**	**2080**	**190**						
Earthfill with filter	**1.5**	**190**	**37**						
Earthfill with rock toe	**8.9**	**1160**	**160**						
Zoned earthfill	**1.2**	**160**	**25**						
Zoned earth and rockfill	**1.2**	**150**	**24**						
Central core earth and rockfill	**(<1.1)**	**(<140)**	**(<34)**	**1.7**	**255**	**19**	**0.18**	**19**	**4**
Concrete face earthfill	**5.3**	**690**	**75**						
Concrete face rockfill	**(<1)**	**(<130)**	**(<17)**						
Puddle core earthfill	**9.3**	**1200**	**38**						
Earthfill with corewall	**(<1)**	**(<130)**	**(<8)**						
Rockfill with corewall	**(<1)**	**(<130)**	**(<13)**						
Hydraulic fill	**(<1)**	**(<130)**	**(<5)**						
ALL DAMS	**3.5**	**450**	**56**	**1.7**	**255**	**19**	**0.18**	**19**	**4**

Notes: (1) P_{Te}, P_{Tf}, and P_{Tef} are the average probabilities of failure over the life of the dam.
(2) P_e, P_f and P_{ef} are the average annual probabilities of failure.
Ref: Foster, Fell, & Spanagle 1998.

Table H-2
(Table 11.2 UNSW): Summary of the Weighting Factors for Piping Through the Embankment Mode of Failure.

FACTOR	GENERAL FACTORS INFLUENCING LIKELIHOOD OF FAILURE				
	MUCH MORE LIKELY	MORE LIKELY	NEUTRAL	LESS LIKELY	MUCH LESS LIKELY
ZONING	Refer to Table 11.1 for the average annual probabilities of failure by piping through the embankment depending on zoning type				
EMBANKMENT FILTERS $W_{E(filt)}$		No embankment filter (for dams which usually have filters (refer to text) (2)	Other dam types (1)	Embankment filter present - poor quality (0.2)	Embankment filter present - well designed and constructed (0.02)
CORE GEOLOGICAL ORIGIN $W_{E(cgo)}$	Alluvial (1.5)	Aeolian, Colluvial (1.25)	Residual, Lacustrine, Marine, Volcanic (1.0)		Glacial (0.5)
CORE SOIL TYPE $W_{E(cst)}$	Dispersive clays (5) Low plasticity silts (ML) (2.5) Poorly and well graded sands (SP, SW) (2)	Clayey and silty sands (SC, SM) (1.2)	Well graded and poorly graded gravels (GW, GP) (1.0) High plasticity silts (MH) (1.0)	Clayey and silty gravels (GC< GM) (0.8) Low plasticity clays (CL) (0.8)	High plasticity clays (CH) (0.3)
COMPACTION $W_{E(cc)}$	No formal compaction (5)	Rolled, modest control (1.2)	Puddle, Hydraulic fill (1.0)		Rolled, good control (0.5)
CONDUITS $W_{E (con)}$	Conduit through the embankment – many poor details (5)	Conduit through the embankment - some poor details (2)	Conduit through embankment - typical USBR practice (1.0)	Conduit through embankment - including downstream filters (0.8)	No conduit through the embankment (0.5)
FOUNDATION TREATMENT $W_{E(FT)}$	Untreated vertical faces or overhangs in core foundation (2)	Irregularities in foundation or abutment, Steep abutments (1.2)		Careful slope modification by cutting, filling with concrete (0.9)	
OBSERVATIONS OF SEEPAGE $W_{E(obs)}$	Muddy leakage Sudden increases in leakage (Up to 10)	Leakage gradually increasing, clear, Sinkholes, Seepage emerging on downstream slope (2)	Leakage steady, clear or not observed (1.0)	Minor leakage (0.7)	Leakage measures none or very small (0.5)
MONITORING AND SURVEILLANCE $W_{E(mon)}$	Inspections annually (2)	Inspections monthly (1.2)	Irregular seepage observations, inspections weekly (1.0)	Weekly - monthly seepage monitoring, weekly inspections (0.8)	Daily monitoring of seepage, daily inspections (0.5)

Ref : Foster, Fell, & Spanagle 1998.

Table H-3
(Table 11.3 UNSW): Summary of Weighting Factors for Piping Through the Foundation Mode of Failure.

FACTOR	GENERAL FACTORS INFLUENCING LIKELIHOOD OF FAILURE				
	MUCH MORE LIKELY	MORE LIKELY	NEUTRAL	LESS LIKELY	MUCH LESS LIKELY
ZONING	Refer to Table 11.1 for the average annual probability of failure by piping through the foundation				
FILTERS $W_{F(filt)}$		No foundation filter present when required (1.2)	No foundation filter (1.0)	Foundation filter(s) present (0.8)	
FOUNDATION TYPE (below cutoff) $W_{F(fnd)}$	Soil foundation (5)		Rock – clay infilled or open fractures and/or erodible rock substance (1.0)	Better rock quality	Rock - closed fractures and non-erodible substance (0.05)
CUTOFF TYPE (Soil foundation) $W_{F(cts)}$ OR CUTOFF TYPE (Rockfill foundation) $W_{F(ctr)}$	Sheetpile wall Poorly constructed diaphragm wall (3)	Shallow or no cutoff trench (1.2) Well constructed diaphragm wall (1.5)	Partially penetrating sheetpile wall or poorly constructed slurry trench wall (1.0) Average cutoff trench (1.0)	Upstream blanket, Partially penetrating well constructed slurry trench wall (0.8) Well constr4ucted cutoff trench (0.9)	Partially penetrating deep cutoff trench (0.7)
SOIL GEOLOGY TYPES (below cutoff) $W_{F(sg)}$ OR ROCK GEOLOGY TYPES (below cutoff) $W_{F(rg)}$	Dispersive soils (5) Volcanic ash (5) Limestone (5) Dolomite (3) Saline (gypsum) (5) Basalt (3)	Residual (1.2) Tuff (1.5) Rhyolite (2) Marble (2) Quartzite (2)	Aeolian, Colluvial, Lacustrine, Marine (1.0)	Alluvial (0.9) Sandstone, Shale, Siltstone, Claystone, Mudstone, Hornfels (0.7) Agglomerate, Volc. Breccia (0.8)	Glacial (0.5) Conglomerate (0.5) Andesite, Gabbro (0.5) Granite, Gneiss (0.2) Schist, Phyllite, Slate (0.5)
OBSERVATIONS OF SEEPAGE $W_{F(obs)}$ OR OBSERVATIONS OF PORE PRESSURES $W_{F(obp)}$	Muddy leakage Sudden increases in leakage (up to 10) Sudden increases in pressures (up to 10)	Leakage gradually increasing, clear, Sinkholes, Sandboils (2) Gradually increasing pressures in foundation (2)	Leakage steady, clear or not observed (1.0) High pressures measured in foundation (1.0)	Minor leakage (0.7)	Leakage measures none or very small (0.5) Low pore pressures in foundation (0.8)
MONITORING AND SURVEILLANCE $W_{F(mon)}$	Inspections annually (2)	Inspections monthly (1.2)	Irregular seepage observations, inspections weekly (1.0)	Weekly - monthly seepage monitoring, weekly inspections (0.8)	Daily monitoring of seepage, daily inspections (0.5)

Ref: Foster, Fell, & Spanagle 1998.

Table H-4
(Table 11.4 UNSW): Summary of Weighting Factors for Piping from the Embankment into the Foundation - Accidents and Failures.
SHEET 1 of 2

FACTOR	GENERAL FACTORS INFLUENCING LIKELIHOOD OF INITIATION OF PIPING - ACCIDENTS AND FAILURES				
	MUCH MORE LIKELY	MORE LIKELY	NEUTRAL	LESS LIKELY	MUCH LESS LIKELY
ZONING	Refer to Table 11.1 for the average annual probability of failure by piping from embankment into foundation				
FILTERS $W_{EF(filt)}$	Appears to be independent of presence/absence of embankment or foundation filters (1.0)				
FOUNDATION CUTOFF TRENCH $W_{EF(cot)}$	Deep and narrow cutoff trench (1.5)		Average cutoff trench width and depth (1.0)	Shallow or no cutoff trench (0.8)	
FOUNDATION TYPE $W_{EF\ (fnd)}$		Founding on or partly on rock foundations (1.5)			Founding on or partly on soil foundations (0.5)
EROSION CONTROL MEASURES OF CORE FOUNDATION $W_{EF\ (ecm)}$	No erosion control measures, open jointed bedrock or open work gravels (up to 5)	No erosion control measures, average foundation conditions (1.2)	No erosion control measures, good foundation conditions (1.0)	Erosion control measures present, poor foundations (0.5)	Good to very good erosion control measures present and good foundation (0.3 - 0.1)
GROUTING OF FOUNDATIONS $W_{EF(gr)}$		No grouting on rock foundations (1.3)	Soil foundation only - not applicable (1.0)	Rock foundations grouted (0.8)	
SOIL GEOLOGY TYPES $W_{EF(sg)}$, OR ROCK GEOLOGY TYPES $W_{EF(rg)}$	Colluvial (5) Sandstone interbedded with shale or limestone (3) Limestone, gypsum (2.5)	Glacial (2) Dolomite, Tuff, Quartzite (1.5) Rhyolite, Basalt, Marble (1.2)	Agglomerate, Volcanic breccia Granite, Andesite, Gabbro, Gneiss (1.0)	Residual (0.8) Sandstone, Conglomerate (0.8) Schist, Phyllite, Slate, Hornfels (0.6)	Alluvial, Aeolian, Lacustrine, Marine, Volcanic (0.5) Shale, Siltstone, Mudstone, Claystone (0.2)

Ref: Foster, Fell, & Spanagle 1998.

Table H-4 (Continued)
(Table 11.4 UNSW) (continued): Summary of Weighting Factors for Piping from the Embankment into the Foundation - Accidents and Failures.
SHEET 2 of 2

FACTOR	GENERAL FACTORS INFLUENCING LIKELIHOOD OF INITIATION OF PIPING - ACCIDENTS AND FAILURES				
	MUCH MORE LIKELY	MORE LIKELY	NEUTRAL	LESS LIKELY	MUCH LESS LIKELY
CORE GEOLOGICAL ORIGIN $W_{EF(cgo)}$	Alluvial (1.5)	Acolian, Colluvial (1.25)	Residual, Lacustrine, Marine, Volcanic (1.0)		Glacial (0.5)
CORE SOI L TYPE $W_{EF\ (cst)}$	Dispersive clays (5) Low plasticity silts (ML) (2.5) Poorly and well graded sands (SP, SW) (2)	Clayey and silty sands (SC, SM) (1.2)	Well graded and poorly graded gravels (CW, CP) (1.0) High plasticity silts (MH) (1.0)	Clayey and silty gravels (GC, GM) (0.8) Low plasticity clays (CL) (0.8)	High plasticity clays (CH) (0.3)
CORE COMPACTION $W_{EF\ (cc)}$	Appears to be independent of compaction – all compaction types (1.0)				
FOUNDATION TREATMENT $W_{EF(ft)}$	Untreated vertical faces or overhangs in core foundation (1.5)	Irregularities in foundation or abutment, Steep abutments (1.1)		Careful slope modification by cutting, filling with concrete (0.9)	
OBSERVATIONS OF SEEPAGE $W_{EF(obs)}$	Muddy leakage, Sudden increases in leakage (up to 10)	Leakage gradually increasing, clear, Sinkholes (2)	Leakage steady, clear or not monitored (1.0)	Minor leakage (0.7)	Leakage measured none or very small (0.5)
MONITORING AND SURVEILLANCE $W_{EF(mon)}$	Inspections annually (2)	Inspections monthly (1.2)	Irregular seepage observations, inspections weekly (1.0)	Weekly - monthly seepage monitoring, weekly inspections (0.8)	Daily monitoring of seepage, daily inspections (0.5)

Ref: Foster, Fell, & Spanagle 1998.